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13. ABSTRACT *(Maximum 200 words)*

We have developed a novel high-efficiency 94 GHz staring monopulse receiver. The receiver is based on four coplanar-waveguide fed(cpw) slot-ring antennas followed by four cpw-based subharmonic mixers which are pumped by a coaxial/cpw 45-46 GHz local oscillator distribution network. The 2-4 GHz IF outputs are amplified and sent to a passive IF monopulse network which synthesizes the sum and difference patterns. The staring monopulse configuration is compatible with MMIC processing and can be fabricated at very low cost for large volume applications. Furthermore, this topology is easily extendable to fully polarimetric monopulse systems at 94 GHz. We have succeeded in building the 2x2 antenna array and in demonstrating 25 dB polarization isolation between the polarized ports. We have also fabricated a 7 dB subharmonic mixer which is, to our knowledge, the best 94 GHz MMIC mixer available to date. The monopulse IF network resulted in better than 30 dB null over a 1 GHz bandwidth. We believe that this design will lead to a low cost implementation of polarimetric W-band monopulse systems and are pursuing the effort under a continuing ARO contract.

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Development of an Integrated 94 GHz Staring Monopulse Receiver

FINAL REPORT

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Graduate Students: Sanjay Raman and N. Scott Barker

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1 Statement of the Problem Studied

The purpose of the NSWC research effort is to develop a high-efficiency monolithic 94 GHz Staring Monopulse Receiver for ship defense applications. The receiver should be compatible with MMIC technology for low-cost, high volume applications and fit within a 65 mm munition. The receiver downconverts the received 94 GHz radiation into three IF channels: sum (Σ), difference in elevation (Δ_{el}), and difference in azimuth (Δ_{az}). These channels are used for high accuracy monopulse tracking.

The preliminary specifications of the staring monopulse receiver are given below:

- Center frequency: 94 GHz
- Bandwidth: 2 GHz
- High efficiency, low noise design (12 dB SSB system noise figure)
- Focal plane design with beamwidths given by the final lens aperture (65 mm at 94 GHz)

1.1 System Description

The system chosen by the University of Michigan is a coplanar waveguide (CPW)-fed planar antenna receiver integrated on a silicon substrate hyperhemispherical lens. The dielectric lens results in unidirectional, high-gain patterns, and eliminates loss to substrate modes. It also provides a strong mechanical support and heat sink for the MMIC receiver. The MMIC receiver itself consists of a 2x2 array of four antennas integrated with four subharmonic mixers which are pumped by a coaxial/cpw 45-46 GHz local oscillator (LO) distribution network. The 2-4 GHz IF outputs from the four mixers are amplified on the MMIC receiver and sent, via four coaxial cables, to a passive 2-4 GHz IF monopulse processing network. The three IF outputs are the 2-4 GHz sum and difference channels.

2 Summary of the Most Important Results

2.1 Uniplanar Antenna Design

2.1.1 Antenna Element

Several CPW-fed slot-type antennas were investigated for this project (double-slot, folded-slot, and slot-ring antennas) [1], [2]. We ultimately chose the slot-ring antenna since it allows very compact spacing in a 2x2 array for monopulse applications and offers the possibility of extension to a fully polarimetric design. A slot-ring antenna placed on a 24 mm ($\sim$ 1 in.) silicon lens at the synthesized elliptical position results in a directivity of 27 dB. With this configuration, there

is a -2.7 dB reflection at the lens-air interference which can be reduced by approximately 1.5 dB by incorporating a quarter-wave matching cap layer. The CPW-fed slot-ring antenna has been extensively studied experimentally and by using the method-of-moments [6], [9]. A slot width of 20 μm and ring radius of 228 μm results in resonant impedance of 120 Ω at 92.6 GHz. The antenna impedance can be matched to 50 Ω using a straightforward $\lambda/4$ cpw transformer over a 20% bandwidth. The measured antenna patterns agree well with theory and show a symmetrical main beam with sidelobe levels below -15 dB from 92-98 GHz and a cross-polarization level in the 45° plane below -21 dB at 94 GHz. The CPW feed was shown to have a negligible effect on the millimeter-wave patterns.

2.1.2 Monopulse Array

A 2x2 array of slot-ring antennas is then constructed with a separation of $0.8\lambda_d$ so as to avoid grating lobes in the dielectric lens along the ground-plane direction. The measured patterns at 94 GHz show the desired 3 dB crossover in both the azimuth and elevation scans. The monopulse response will be formed from the sum and difference of these patterns. The near-field mutual coupling mutual between the elements in the 2x2 array has been studied using the method of moments. In the sum mode with a $0.8\lambda_d$ element spacing the mutual impedance is found to be approximately 4 + j3 Ω at the single-element resonant frequency, a relatively minor effect on the driving point impedance of the individual antennas.

2.1.3 Dual-Polarized Designs

The slot-ring antenna can also support two orthogonal modes when fed by two ports located 90° apart around the circumference of the ring. The measured isolation is better than -25 dB over the 86-92 GHz frequency range. For millimeter-wave pattern measurements a dual polarized slot-ring antenna was fabricated with a metal-insulator-metal split capacitor across the center ground plane to DC isolate the two bolometer detectors. The measured patterns show better than -20 dB cross-polarization isolation between the two ports over the 94-100 GHz range. The non-zero cross-polarization level on boresight is attributed to the split capacitor across the center of the antenna.

2.2 Uniplanar 94 GHz Schottky Diode Mixers

We have designed, fabricated, and tested a W-band 2x Schottky diode subharmonic mixer [4], [8]. The mixer is realized in uniplanar CPW technology to be compatible with the dielectric lens supported slot-ring antennas, and utilizes a University of Virginia SC1T7D20 antiparallel Schottky diode pair. The circuit is designed to operate at RF frequencies of 92-96 GHz, IF frequencies of 2-4 GHz, and LO frequencies of 45-46 GHz. The total size of the mixer circuits without matching networks is 0.8 mm x 1.5 mm, excluding probe pads and transitions. The measured minimum SSB conversion loss is 7.0 dB at RF of 94 GHz, an IF of 2-4 GHz, and an LO power of 8 dBm (6.3 mW). This represents state-of-the-art performance for a planar W-band subharmonic mixer, and is even

competitive with fundamental planar Schottky diode mixers. The mixer is broadband with a SSB conversion loss of less than 10 dB over the 83-97 GHz measurement band. The measured LO-RF isolation is better than -40 dB for LO frequencies of 45-46 GHz, which is important in receiver applications to minimize radiation of LO power from the RF port. The DSB noise temperature using the Y-factor method is 725 K at an LO frequency of 45.5 GHz and an IF of 1.4 GHz, and is expected to have a minimum value of 650 K at 94 GHz. The incorporation of simple single-stub matching network results in an improved LO match, with low conversion loss from 4 dBm (2.5 mW) to 12 dBm (15.8 mW). This represents the lowest LO power requirement of any planar W-band mixer to date. The measured data agrees well with the predicted performance using harmonic balance analysis.

2.3 Single- and Dual-Polarized Slot-Ring Receivers

Finally, we have integrated the uniplanar subharonic mixers with the single- and dual-polarized slot-ring antennas to realize prototype receiver channels. The DSB receiver noise temperature measured using the Y-factor method is 4300 K (12 dB noise figure) at an LO frequency of 45.0 GHz and an IF of 1.4 GHz. This includes lens reflection (2.7 dB) and absorption (0.2-0.4 dB) losses, backside radiation (0.2 dB), RF feedline loss (1.25 dB), and RF mismatch between the antenna and the mixer. When these losses are deembedded from the measurements the results are in good agreement with the measured performance of the uniplanar subharmonic mixer alone. The refelction loss will be reduced with an improved matching network design resulting in a DSB noise temperature of 1700-1900 K and a conversion loss of 8-9 dB which will meet the specifications for the receiver. We are currently awaiting a lens with an optimal machined quarter-wave matching layer, and are redesigning the RF matching network. Once the performance of the individual channels is verfied, it is a straightforward matter to integrate them in a 2 x 2 array.

2.4 IF Monopulse Processor

We have studied several IF monopulse processor network configurations based on mircostrip branch-line couplers and Lange couplers. It is immediately apparent from the simulated system response that the branch-line couplers do not provide a wide bandwidth for the sum and difference channels and therefore the design was abandoned. However, the Lange couplers do provide an excellent difference channel response with a 1 GHz 20 dB null bandwidth and less than 1 dB variation in the sum pattern. It is interesting to note that the Lange coupler network that we designed provided a difference port with a 2 GHz 18-dB null bandwidth and a 1 GHz 30-dB null bandwidth [10]. This channel can be used for high performance monopulse design.

We have also constructed a monopulse stripline network out of commercial M/ACOM couplers and line stretchers. The measured response shows less than 1 dB variation in the sum port over a 2 GHz bandwidth and a 2 GHz 25-dB null bandwidth. With a reduced bandwidth of 1 GHz, the difference null drops to 30 dB and deeper nulls can be further achieved with more reductions in the bandwidth.

2.5 Local Oscillator

We have obtained a 46 GHz Gunn Oscillator with a 200 mW RF output power and varactor tuning over a 1 GHz bandwidth as well as the necessary U-band coaxial connectors and cables. The LO from the Gunn is power divided using the 0°/180° ports of a waveguide magic-Tee. The 180° phase difference provided by the magic-Tee compensates for the 180° phase difference due to the monopulse receiver antenna layout. The LO is then sent to the receiver where it is divided using Wilkinson power dividers.

2.6 Extension to Polarimetric Monopulse Receivers

The extension to a fully polarimetric receiver is straight forward, as has been demonstrated by the work done on the dual-polarized slot-ring antenna. There are two basic topologies used in polarimetric receivers. The traditional topology processes the polarimetric signals at the RF frequency. This involves using RF variable phase shifters and variable attenuators which are expensive and add considerable design complexity. The other topology downconverts both polarizations from the dual-polarized antenna to the IF, and the signals are then processed using an IF network. In this case, the variable phase shifters and variable attenuators operate at the IF frequency and can be off-the-shelf commercial components. Another important advantage of this topology is that after amplification, the IF signals can be divided into several ports which provide the ability to measure many different polarizations simulataneously.

The main drawback to this topology is that it requires a mixer for each polarimetric signal. Therefore, a phased array consisting of many antenna elements would never use this design, however, a 2x2 monopulse array only requires eight mixers. Therefore, we believe that the advantages of simultaneous evaluation of many different polarization states outweigh the cost of the additional mixers and LO distribution network. Furthermore, since the dielectric lens system is being used, high gain patterns are possible without the need for a large number of elements across the aperture.

We have designed and tested a 10 GHz dual polarized microstrip antenna system in order to demonstrate the advantages of a polarization agile receiver. We have proven that such a system can receive any polarization state [5]. We have also tested the polarimetric accuracy of the system and found it to be with ±5° of the incident polarization [7]. The knowledge of the incident polarization could be used to determine more information about the target and the presence of decoy tactics such as chaff. It could also help eliminate the polarimetric response of clutter.

3 Technology Transfer

Since the beginning of this contract, we have had close cooperation with two large U.S. Defense Companies; Lockheed Martin and Northrup Grumman. Both of these companies have shown considerable interests in our project. The details of our interaction is summarized below:

Lockheed Martin:
Contact persons: Dr. Norm Byer and Dr. Jim Sowers.

The relationship with Lockheed Martin has been very close and we have signed mutual non-disclosure agreements. Under sponsorship from NSWC, Lockheed Martin developed a 94 GHz 64-element phased array for missile front-ends. This topology offers a more versatile but more expensive solution to the focal-plane staring monopulse receiver developed by UM. However, Lokcheed Martin has shown considerable interest in our low-cost design, and is ready to build the staring monopulse system with their newly developed PALNA (Power Amplifier Low Noise Amplifier) chips. In this case, the monopulse front-end will be able to function in both transmit and receive modes. Furthermore, Lockheed Martin is integrating our successful subharmonic mixer using their Schottky-diode MMIC technology. The mixers are expected to be fabricated in January/February 1997. The relationship with Lockheed Martin has therefore been a successful one and will hopefully lead to new contracts with NSWC/DARPA for 35 GHz and 94 GHz monopulse systems.

Northrup Grumman:
Contact Person: Norm Powell

The relationship with Northrup Grumman has also been close but specifically targeted to the development of a micromachined-based phase plate. In this case, Northrup Grumman had a microstrip-based antenna design and we acted as consultants to their project. Until now, there has been no demonstration of a phase-plate from Northrup Grumman due to problems with the design and fabrication of the first W-band phase shifter. The phase-shifter was subsequently changed by Northrup Grumman and a new iteration is currently being fabricated. Northrup Grumman was awarded a $1.0 Million dollar project from DARPA (Jan. 1997) for the demonstration of this technology, and we may be working with them on the design and measurement of a new phase plate.

4 Inventions

1. Single- and Dual-Polarized CPW-fed Slot-Ring Antennas: See Ref. [6].
2. Fully Polarimetric Monopulse Receiver: See Ref. [3].
3. Wideband Planar Monopulse Processor: See Ref. [7].

5 Participating Scientific Personnel: Advanced Degrees, Honors and Awards Received

Gabriel M. Rebeiz, Ph.D., Associate Professor, Electrical Engineering and Computer Science Department, The University of Michigan.

Linda P.B. Katehi, Ph.D., Professor, Electrical Engineering and Computer Science Department, The University of Michigan.

Sanjay Raman, Graduate Student/Research Assistant, Electrical Engineering and Computer Science Department, The University of Michigan Mr. Raman received the Best Student Paper Awards at the 1995 IEEE Antennas and Propagation Symposium, Newport Beach, CA, and the 1996 IEEE MTT-S International Microwave Symposium, San Francisco, CA, and was a co-winner of the 1996 Armed Forces Communications Electronics Association (AFCEA) postgraduate fellowship.

N. Scott Barker, Graduate Student/Research Assistant, Electrical Engineering and Computer Science Department, The University of Michigan Mr. Barker received the M.S.E.E. degree from the University of Michigan in December 1996.

6 List of All Publications and Technical Reports Published

[1] S. Raman and G.M. Rebeiz, "94 GHz Slot-Ring Antennas for monopulse applications," *1995 IEEE Antennas and Propagation Intl. Symp. Dig.*, Newport Beach, CA, June 18-23, 1995, pp. 722-725.

[2] S. Raman, T.M. Weller, L.P. Katehi, and G.M. Rebeiz, "A Double- Folded Slot Antenna at 94 GHz," *1995 IEEE Antennas and Propagation Intl. Symp. Dig.*, Newport Beach, CA, June 18-23, 1995, pp. 710-713.

[3] S. Raman and G.M. Rebeiz, "Integrated Millimeter-Wave Polarimetric Radar Receivers," *Proc. of the 1996 IEEE National Radar Conference*, Ann Arbor, MI, May 13-16, 1996, pp. 232-237.

[4] S. Raman and G.M. Rebeiz, "A 94 GHz Uniplanar Subharmonic Mixer," *1996 IEEE MTT-S Int. Microwave Symp. Dig.*, San Francisco, CA, June 17-21, 1996, pp. 385-388.

[5] N. Scott Barker and G.M. Rebeiz, "Planar Front-Ends With Polarization Agile IF systems," *1996 IEEE Antennas and Propagation Intl. Symp. Dig.*, Baltimore, MA, July 1996 pp. 1532-1535.

[6] S. Raman and G.M. Rebeiz, "Single- and dual-polarized Millimeter-Wave Slot-Ring Antennas," *IEEE Trans. on Antennas and Propagation*, Vol. 44, No. 11, November 1996, pp. 1438-1444.

[7] N. Scott Barker and G.M. Rebeiz, "IF-Based Polarimetric Receivers," *To appear in IEEE Microwave and Guided Wave Letters*, Vol. 7, No. 3, March 1997.

[8] S. Raman, F. Rucky and G.M. Rebeiz, "A High Performance W-Band Uniplanar Subharmonic Mixer," *Accepted for publication in IEEE Trans. on Microwave Theory and Techniques.*

[9] S. Raman and G.M. Rebeiz, "Single- and Dual-Polarized Slot-Ring Subharmonic Receivers," *Submitted to the 1997 IEEE MTT-S Int. Microwave Symp.*, Dec. 1996.

[10] N. Scott Barker and G.M. Rebeiz, "An Octave Bandwidth Monopulse Processor," *Submitted to the 1997 IEEE MTT-S Int. Microwave Symp.*, Dec. 1996.